

Lifshitz metric with hyperscaling violation from NS5- Dp states in string theory

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Abstract

In previous papers [1, 2] we have shown how Lifshitz-like space-time (space-time having a Lifshitz scaling along with a hyperscaling violation) can arise by taking near horizon limits of certain intersecting solutions (F-string with Dp -branes and also with two D-branes) of string theory. In this paper we construct intersecting bound state solutions in the form of NS5- Dp -branes (with $1 \leq p \leq 6$) of type II string theories. These are 1/4 BPS and threshold bound states unlike the known NS5- Dp bound states which are 1/2 BPS and non-threshold. We show that the near horizon limits of these solutions also lead to Lifshitz-like space-time with the dynamical scaling exponent $z = 0$ and the hyperscaling violation exponent $\theta = 9 - p$. The spatial dimension of the boundary theory is $d = 7 - p$. The dilatons in these theories are not constant in general (except for $p = 5$) and therefore produce RG flows. So, we also consider the strong coupling phases of these theories and find that these phases also have similar Lifshitz-like structures, except for $p = 2$, where it has an AdS_3 structure.

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1 Introduction

It is well-known that string theory admits various kinds of spatially extended solutions, generically called branes, which preserve certain fraction of space-time supersymmetries. These solutions may be constituted of a single type of brane or a composite of more than one type of branes. They have been proved quite useful as string theory in the near horizon geometry (a kind of low energy limit) of a stack of coincident branes can be seen to be holographically dual to a theory without gravity living on the boundary. This is a strong-weak duality and so one can gain insight about the strongly coupled field theory by studying the weakly coupled string or supergravity theory [3, 4, 5, 6]. For D3-brane this is the AdS/CFT correspondence of Maldacena [3] where the boundary theory is four dimensional, $\mathcal{N} = 4$, $SU(N)$ super Yang-Mills theory (which is conformal). Similar correspondence is also believed to hold for other types of branes which goes by the name gauge/gravity duality [6]. So, for example, for Dp -branes, the boundary theory is $(p+1)$ -dimensional super Yang-Mills theory (which is non-conformal) with 16 supercharges [7].

Similar correspondence holds good even for the composite brane states. Composite brane solutions also known as intersecting branes could be of different types. So, for example, there are 1/2 BPS non-threshold types, such as, $D(p-2)$ - Dp [8, 9, 10] (for $1 \leq p \leq 6$), F - Dp [11] (for $1 \leq p \leq 7$) and $NS5$ - Dp [12, 13, 14] (for $0 \leq p \leq 5$) among others. In the near horizon limit (or decoupling limit) they give rise to some non-gravitational, non-local theories on the boundary. For $D(p-2)$ - Dp , we get noncommutative Yang-Mills (NCYM) theory in $(p+1)$ -dimensions [15, 16], for F - Dp we get $(p+1)$ -dimensional noncommutative open string (NCOS) theory [17, 18] and for $NS5$ - Dp we get six dimensional open Dp -brane (OD p) theory [19]. So, one can gain insight about these non-local theories, in the strongly coupled regime, by studying the gravity duals. The other type of composite brane solutions are the 1/4 BPS and threshold intersecting brane solutions [20, 21, 22]. These are $D(p-4)$ - Dp (for $3 \leq p \leq 6$) and we have also found some new solutions F - Dp (for $0 \leq p \leq 5$) [1], $D(p-2)$ - Dp (for $3 \leq p \leq 5$) and Dp - Dp' (for $2 \leq p \leq 4$) [2]. All these solutions (except some), as we have seen, give rise to Lifshitz-like space-time in the near horizon limit³. It is known that Lifshitz scaling symmetry, which is a non-relativistic symmetry, arise as a possible symmetry in some condensed matter systems at quantum critical point [40, 41]. So, it may be the case that the space-time we obtain from these intersecting bound state solutions in the near horizon limit are the gravity duals of such condensed matter systems near quantum critical point and since the latter systems are strongly coupled, we can learn about the phase structures by studying the gravity solutions in the spirit of AdS/CFT correspondence.

³The concept of hyperscaling violation was introduced in the context of random field Ising system in [23]. In gauge/gravity duality this was identified while describing certain metallic states with hidden fermi surface in [24, 25]. More general gravity solutions having Lifshitz scaling alongwith hyperscaling violation have been found and studied in [26, 27, 28, 29, 30, 31, 32, 1, 2, 33, 34, 35, 36, 37, 38, 39].

In this paper we construct another kind of 1/4 BPS threshold intersecting brane solutions of type II string theories in the form of NS5-D p (for $1 \leq p \leq 6$) solutions. These solutions in the near horizon limit give rise to Lifshitz-like space-time and may describe the gravity dual of some condensed matter systems near quantum critical point (unlike the standard NS5-D p which in the near horizon limit gives rise to OD p theories [19, 13, 14] , mentioned earlier). The construction proceeds from the F-D5 solution we have obtained in [1]. Then taking an S-duality on that solution gives NS5-D1 solution. Further T-dualities along the spatial directions of NS5-brane yield all the NS5-D p solutions which are 1/4 BPS and threshold solutions. Then taking the near horizon limit and going to a suitable coordinate we get the Lifshitz space-time with hyperscaling violation where the dynamical critical exponent we find is $z = 0$ and the hyperscaling violation exponent is $\theta = 9 - p$. The spatial dimension of the boundary theory is given as $d = 7 - p$. These values of (z, θ, d) are shown to satisfy the null energy condition (NEC) [29] so that they may give sensible dual theories. We have seen that the dilatons for these solutions are in general non-constant except for $p = 5$ and therefore produce RG flows. We also construct the strongly coupled phases of these solutions either by going to the S-dual frame (for type IIB solutions) or by uplifting the solutions to M-theory (for type IIA solutions). These strongly coupled phases also have similar Lifshitz-like structures except for $p = 2$, where the M-theory lift of the NS5-D2 solution has AdS₃ structure in the near horizon limit.

This paper is organized as follows. In the next section, we give the construction of NS5-D p solutions of type II string theories and show that their near horizon limit gives rise to Lifshitz-like space-time. In section 3 we discuss the RG flows and give the strongly coupled phases of the various solutions obtained in the previous section. Then we conclude in section 4.

2 NS5-D p and Lifshitz-like space-time

In this section we first construct the 1/4 BPS threshold NS5-D p bound state solution of type II string theories and then by taking the near horizon limit we will show how they lead to Lifshitz-like space-time in a suitable coordinate. For that we will start from the F-D5 solution obtained in eq.(2.6) of [1]. For $p = 5$, the F-D p solution given there takes the form,

$$\begin{aligned}
ds^2 &= H_2^{\frac{1}{2}} \left[-\frac{dt^2}{H_1 H_2} + \frac{\sum_{i=1}^5 (dx^i)^2}{H_2} + \frac{(dx^6)^2}{H_1} + dr^2 + r^2 d\Omega_2^2 \right] \\
e^{2\phi} &= \frac{1}{H_1 H_2} \\
B_{[2]} &= (1 - H_1^{-1}) dt \wedge dx^6, \quad A_{[6]} = (1 - H_2^{-1}) dt \wedge dx^1 \wedge \cdots \wedge dx^5
\end{aligned} \tag{1}$$

Here the two harmonic functions are given as, $H_{1,2} = 1 + Q_{1,2}/r$, with $Q_{1,2}$ denoting the charges of the F-string and D5-brane respectively. It is clear from (1) that F-string is lying along x^6 and D5-brane is lying along x^1, \dots, x^5 . Also $B_{[2]}$ is the NSNS form field which couples to F-string and $A_{[6]}$ is the RR 6-form gauge field which couples to D5-brane. Taking an S-duality on this solution we get NS5-D1 solution and has the form,

$$\begin{aligned} ds^2 &= H_1^{\frac{1}{2}} H_2 \left[-\frac{dt^2}{H_1 H_2} + \frac{\sum_{i=1}^5 (dx^i)^2}{H_2} + \frac{(dx^6)^2}{H_1} + dr^2 + r^2 d\Omega_2^2 \right] \\ e^{2\phi} &= H_1 H_2 \\ A_{[2]} &= (1 - H_1^{-1}) dt \wedge dx^6, \quad H_{[3]} = -Q_2 \text{Vol}(\Omega_2) \wedge dx^6 \end{aligned} \quad (2)$$

Like in (1) the metric here is also given in the string frame. $A_{[2]}$ is the RR 2-form which couples to the D-string lying along x^6 and $H_{[3]}$ is the NSNS magnetic 3-form field strength which couples to NS5-brane lying along x^1, \dots, x^5 . Harmonic functions $H_{1,2}$ remain the same as given above. Now taking T-dualities along the NS5 brane directions we generate all the other NS5-D p solutions which can be written in the following compact form,

$$\begin{aligned} ds^2 &= H_1^{\frac{1}{2}} H_2 \left[-\frac{dt^2}{H_1 H_2} + \frac{\sum_{i=2}^p (dx^i)^2}{H_1 H_2} + \frac{(dx^1)^2}{H_1} + \frac{\sum_{j=p+1}^6 (dx^j)^2}{H_2} + dr^2 + r^2 d\Omega_2^2 \right] \\ e^{2\phi} &= H_1^{\frac{3-p}{2}} H_2 \\ A_{[p+1]} &= (1 - H_1^{-1}) dt \wedge dx^1 \wedge \dots \wedge dx^p, \quad H_{[3]} = -Q_2 \text{Vol}(\Omega_2) \wedge dx^1 \end{aligned} \quad (3)$$

Here $p = 1, \dots, 6$ and since these solutions are obtained from 1/4 BPS threshold F-D5 solution by the application of S- and T-dualities, these NS5-D p solutions are also 1/4 BPS and threshold. Note that in writing (3) from (2) we have exchanged the coordinates $x^6 \leftrightarrow x^1$ for convenience. Now the D p -brane is along x^1, \dots, x^p and NS5-brane is along x^2, \dots, x^6 and their charges are Q_1 and Q_2 respectively. They overlap on a $(p-1)$ brane along x^2, \dots, x^p . The harmonic functions $H_{1,2}$ remain the same as given before. Next, we take a near horizon limit by approximating $H_{1,2} \approx Q_{1,2}/r$ and substitute in the solution (3). By introducing a new coordinate $u^2 = r$, we can write the NS5-D p solution in the near horizon limit as follows,

$$\begin{aligned} ds^2 &= Q_1^{\frac{1}{2}} Q_2 u \left[-\frac{dt^2}{Q_1 Q_2} + \frac{\sum_{i=2}^p (dx^i)^2}{Q_1 Q_2} + \frac{(dx^1)^2}{Q_1 u^2} + \frac{\sum_{j=p+1}^6 (dx^j)^2}{Q_2 u^2} + 4 \frac{du^2}{u^2} + d\Omega_2^2 \right] \\ e^{2\phi} &= \frac{Q_1^{\frac{3-p}{2}} Q_2}{u^{5-p}} \\ A_{[p+1]} &= -\frac{u^2}{Q_1} dt \wedge dx^1 \wedge \dots \wedge dx^p, \quad H_{[3]} = -Q_2 \text{Vol}(\Omega_2) \wedge dx^1 \end{aligned} \quad (4)$$

It is clear from (4) that under the scaling $t \rightarrow \lambda^0 t$, $x^1 \rightarrow \lambda x^1$, $x^{p+1}, \dots, x^6 \rightarrow \lambda x^{p+1}, \dots, x^6$, $u \rightarrow \lambda u$, the part of the metric in the square bracket remains invariant. But the full metric is not

indicating that there is hyperscaling violation. In order to find the hyperscaling violation exponent θ , we dimensionally reduce the metric on S^2 and also on x^2, \dots, x^p and express the reduced metric in Einstein frame which is given as,

$$ds_{9-p,E}^2 = Q_1^{\frac{2}{7-p}} Q_2 u^{\frac{2(9-p)}{7-p}} \left[-\frac{dt^2}{Q_1 Q_2} + \frac{(dx^1)^2}{Q_1 u^2} + \frac{\sum_{j=p+1}^6 (dx^j)^2}{Q_2 u^2} + 4 \frac{du^2}{u^2} \right] \quad (5)$$

We therefore find that under the above scaling the reduced metric (5) transforms as

$$\begin{aligned} ds_{9-p,E} &\rightarrow \lambda^{(9-p)/(7-p)} ds_{9-p,E} \\ &\equiv \lambda^{\theta/d} ds_{9-p,E} \end{aligned} \quad (6)$$

where $d = 7 - p$ is the spatial dimension of the boundary theory and therefore, from (6) we find the hyperscaling violation exponent to have the value $\theta = 9 - p$. Under the above scaling the other fields transform as,

$$\phi \rightarrow \phi - \frac{5-p}{2} \log \lambda, \quad A_{[p+1]} \rightarrow \lambda^2 A_{[2]}, \quad H_{[3]} \rightarrow \lambda H_{[3]} \quad (7)$$

Therefore, we have shown that the NS5-Dp intersecting brane solutions in the near horizon limit do give rise to Lifshitz-like space-time with $z = 0$, $\theta = 9 - p$ and $d = 7 - p$. It can be easily checked that these values of (z, θ, d) indeed satisfy the following NEC [29],

$$\begin{aligned} (d - \theta)(d(z - 1) - \theta) &\geq 0 \\ (z - 1)(d + z - \theta) &\geq 0 \end{aligned} \quad (8)$$

Similar Lifshitz-like structures have also been obtained for near horizon geometries of F-Dp [1] and also in some intersecting brane solutions [2]. We here give a table for the values of (z, θ, d) of all these solutions for comparison,

Type	z	θ	d
NS5-Dp $1 \leq p \leq 6$	0	$9 - p$	$7 - p$
F-Dp $0 \leq p \leq 5, p \neq 4$	$\frac{2(5-p)}{4-p}$	$p - \frac{p-2}{4-p}$	$p + 1$
D0-D4 D1-D3 D2-D2'	4	2	4
D2-D6 D3-D5 D4-D4'	0	6	4

In the third row, the three intersecting brane solutions D0-D4, D1-D3 and D2-D2' have the same set of values of (z, θ, d) and similarly, in the 4th row D2-D6, D3-D5 and D4-D4' have the same set of values of (z, θ, d) . Among all the solutions only for F-D2 we have $\theta = d - 1$ indicating that the corresponding boundary theory describes compressible metallic states with hidden Fermi surface [24, 25]. The field theoretic meaning of the other scaling solutions are not known.

3 RG flows and phase structures

We have seen in the previous section that the dilatons of NS5-D p solutions are in general not constant except for $p = 5$. Therefore, as u changes, the dilatons can become large and invalidate the supergravity solutions. Also the curvature of the solutions must remain small for the supergravity description to remain valid. These conditions put some restrictions on the parameter u or the energy parameter in the dual field theory. We will discuss them here in a case by case basis.

3.1 NS5-D1

The S-dual of this solution is F-D5 and this case is already discussed in [1] and will not be repeated here. Note that both these solutions have Lifshitz-like structure in the near horizon limit.

3.2 NS5-D2

The near horizon geometry in a suitable coordinate u of this solution is given in (4). From there we find that the dilaton remains small only if $u \gg Q_1^{1/6} Q_2^{1/3}$ and the curvature remains small if $u \gg 1/(Q_1^{1/2} Q_2)$. For large Q_1 and Q_2 if the first condition is satisfied then the second one is automatically satisfied. However, when $u \leq Q_1^{1/6} Q_2^{1/3}$, the dilaton would be large and in order to get a valid supergravity description we need to uplift the solution to M-theory. The solution in this case takes the form,

$$ds^2 = Q_1^{\frac{1}{3}} Q_2^{\frac{2}{3}} \left[\frac{-dt^2 + (dx^2)^2}{Q_1 Q_2 r^2} + \frac{(dx^1)^2}{Q_1} + \frac{\sum_{j=3}^6 (dx^j)^2}{Q_2} + \frac{dr^2}{r^2} + d\Omega_3^2 \right] \quad (9)$$

The above solution represents the near horizon limit of M5-M2 solutions intersecting on a string along x^2 [20]. Note that in writing the solution we have kept the coordinate r (not u). It is obvious that it has an $\text{AdS}_3 \times \text{E}^5 \times \text{S}^3$ structure.

3.3 NS5-D3

The S-dual of this solution is F-D3 and this case is also discussed in [1] and will not be repeated here. Here also both the solutions have Lifshitz-like structure.

3.4 NS5-D4

The geometry of this solution in the near horizon limit is given in (4). From the expression of dilaton we find that it will remain small for $u \gg Q_2/Q_1^{1/2}$ and the curvature remains small for $u \gg 1/(Q_1^{1/2}Q_2)$. For large Q_2 , the first condition is sufficient for supergravity description to remain valid. However, when $u \leq Q_2/Q_1^{1/2}$, we have to uplift the solution to M-theory. The uplifted solution has the form,

$$ds^2 = (Q_1 Q_2)^{\frac{2}{3}} u^{\frac{4}{3}} \left[\frac{-dt^2 + \sum_{i=2}^4 (dx^i)^2}{Q_1 Q_2} + \frac{(dx^1)^2}{Q_1 u^2} + \frac{\sum_{j=5}^6 (dx^j)^2}{Q_2 u^2} + 4 \frac{du^2}{u^2} + d\Omega_2^2 + \frac{(dx^{11})^2}{Q_1 u^2} \right] \quad (10)$$

The above solution represents the near horizon limit of M5-M5' solution intersecting on a 3-brane along x^2, x^3, x^4 [20]. This metric again has a Lifshitz-like structure with ($z = 0, \theta = 6, d = 4$). In obtaining θ we compactify (10) on S^2 and $x^{2,3,4}$ and express the resulting metric in Einstein frame.

3.5 NS5-D5

In the near horizon limit NS5-D5 solution expressed in a suitable coordinate u is given in (4). Here the dilaton is constant. However, the dilaton will remain small as long as $Q_2 \ll Q_1$ and the curvature remains small for $u \gg 1/(Q_1^{1/2}Q_2)$. But, when $Q_2 \geq Q_1$, the dilaton will become large invalidating the supergravity description. In that case we have to go to the S-dual frame. In the S-dual frame the metric takes the form,

$$ds^2 = Q_1 Q_2^{\frac{1}{2}} u \left[\frac{-dt^2 + \sum_{i=2}^5 (dx^i)^2}{Q_1 Q_2} + \frac{(dx^1)^2}{Q_1 u^2} + \frac{(dx^6)^2}{Q_2 u^2} + 4 \frac{du^2}{u^2} + d\Omega_2^2 \right] \quad (11)$$

Again we find that the above S-dual metric has Lifshitz-like structure with ($z = 0, \theta = 4, d = 2$) exactly as those of the original solution.

3.6 NS5-D6

The near horizon limit of this solution in a suitable coordinate u is given in (4). Here the dilaton and the curvature of the metric remain small in the region $1/(Q_1^{1/2}Q_2) \ll u \ll Q_1^{3/2}/Q_2$. However, when $u \geq Q_1^{3/2}/Q_1$, the dilaton becomes large and the supergravity

solution is no longer valid. So, we have to uplift the solution to M-theory. The uplifted solution in this case takes the form,

$$ds^2 = Q_1 Q_2^{\frac{2}{3}} u^{\frac{2}{3}} \left[\frac{-dt^2 + \sum_{i=2}^6 (dx^i)^2}{Q_1 Q_2} + \frac{(dx^1)^2}{Q_1 u^2} + 4 \frac{du^2}{u^2} + d\Omega_2^2 + \frac{(dx^{11} - 2Q_1 \sin^2 \frac{\theta}{2} d\phi)^2}{Q_1^2} \right] \quad (12)$$

The above solution represents the near horizon limit of the intersecting M5-KK solution [42]. It can be easily checked that this solution also has Lifshitz-like structure with ($z = 0$, $\theta = 3$, $d = 1$) as those of the original solution.

4 Conclusion

To conclude, in this paper we have constructed 1/4 BPS, threshold intersecting NS5-D p (for $1 \leq p \leq 6$) brane solutions of type II string theories starting from the 1/4 BPS threshold F-D5 solution given in [1] of type IIB string theory by applying S- and T-dualities. These solutions are different from the known NS5-D p solutions which are 1/2 BPS and non-threshold. Unlike the known NS5-D p solutions which in the near horizon limit leads to six dimensional open D p -brane theory on the boundary, the solutions constructed in this paper give Lifshitz-like space-time, that is, space-time having Lifshitz scaling symmetry along with some hyperscaling violation in the near horizon limit. It is known that some condensed matter system near their quantum critical point show similar kind of scaling symmetry, so, the solutions discussed in this paper may describe the gravity dual of such condensed matter systems near that point. Also since the NS5-D p solution we have obtained are 1/4 BPS, the Lifshitz-like solutions should also preserve at least a 1/4 SUSY. We found that the solutions obtained from NS5-D p have a scaling symmetry with dynamical critical exponent $z = 0$, the hyperscaling violation exponent $\theta = 9 - p$ and the spatial dimensions of the boundary theory $d = 7 - p$. We have seen that these values of (z , θ , d) satisfy NEC indicating that they might lead to a sensible dual theory. As similar structures were obtained for other type of intersecting solutions we have given a table for the comparison. The dilatons for these solutions are not constant except for $p = 5$ and therefore, they give rise to RG flows. We have discussed the various phases of these solutions considering the RG flows. We found that the strongly coupled phases also give Lifshitz-like space-time except for $p = 2$. The strongly coupled phase of the near horizon NS5-D2 solution actually has the structure $\text{AdS}_3 \times \text{E}^5 \times \text{S}^3$. The scaling solutions we have obtained in this paper has dynamical scaling exponent $z = 0$ and thus it appears that there is no relaxation in time of the system described by the boundary theory. It would be interesting to understand the field theoretic meaning and the consequences of these scaling solutions.

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